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DEFENSE COMMUNICATIONS ENGINEERING CENTER

TECHNICAL NOTE NO. 1-87

APPLICATION OF THE NAVSTAR GLOBAL POSITIONING SYSTEM (GPS) TO THE NETWORK SYNCHRONIZATION OF THE DCS

MARCH 1987

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This publication describes the proposed network synchronization capability for the near-term Defense Communications System (DCS), and in particular the methodology for integrating this capability with the evolving NAVSTAR Global Positioning System (GPS). A detailed description of the GPS is provided as well as a discussion as to how it might be applied in the DCS. Finally, a description is given for some of the available, commercial, off-the-shelf, GPS receivers.

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EXECUTIVE SUMMARY

The purpose of this technical note is to provide a description of the NAVSTAR Global Positioning System (GPS), to provide characteristics of some of the available representative GPS equipment, and to assess GPS as a candidate system for DCS timing and synchronization.

The current DCS timing and synchronization equipment being acquired through the U.S. Army provides the required Coordinated Universal Time (UTC) reference via Loran C based systems. The JCS Master Navigation Plan proposes a phase-out of the Loran system in favor of the NAVSTAR Global Positioning System (originally by 1992). However, due to the delay in launch schedule (caused by the Space Shuttle disaster), the GPS is not scheduled to be fully operational before 1994. A transition from the current Loran C based timing systems to one based upon GPS is essential so that the DCS communications requirements can be fully achieved during the post-Loran C period.

Chapter III describes in generic terms the basic configuration of the equipment used to provide the current Loran C network synchronization. The basic configuration is composed of a station clock, clock distribution subsystem, and the digital data buffer. The performance characteristics of this system as well as the performance characteristics of the individual equipments have been well documented [1].

Chapter IV provides a detailed description of the NAVSTAR GPS. This description contains an overview of the implementation plan for the GPS satellites, the three GPS segments (space, ground control, and receiver), and performance data reflecting the high accuracy of GPS.

Chapter V discusses a survey of GPS receivers that would provide for the DCS timing and synchronization requirements. Appendix A is an extension of this chapter and provides technical details concerning some of the available commercial GPS receiver equipment.

Chapter VI is a summation of the criteria for the potential application of GPS within the DCS, and Chapter VII contains conclusions.

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I. INTRODUCTION

The purpose of this technical note is to provide a description of the NAVSTAR Global Positioning System (GPS), to provide characteristics of some of the available representative GPS equipment, and to assess GPS as a candidate system for DCS timing and synchronization.

II. BACKGROUND

Prior to implementation of the Defense Communications System (DCS) timing and synchronization (T&S) equipment, the DCS digital transmission subsystems were timed by clocks intrinsic to the transmission equipment (e.g., clocks within the DRAMA radio) and by use of pulse stuffing and buffering, also intrinsic to the transmission equipment. However, with the introduction of digital switching and certain transmission subsystems, such as the Low Speed Time Division Multiplexer (LSTDM) and digital troposcatter, a timing subsystem was also determined to be required to: (1) satisfy switch system performance requirements, (2) allow synchronous transmission within the low speed digital data network, (3) provide acceptable performance of digital troposcatter by using synchronous interfaces for all levels of multiplex, and (4) provide extension of satellite-derived synchronous circuits into the terrestrial DCS.

DCEC TR 23-77 [2] described the technical performance aspects of the timing subsystem proposed to support the aforementioned near-term synchronous subnetworks in the DCS. This requirement was originally submitted for Military Department consideration in the DCA Five Year Program (FYP 76) and has since been updated annually in each year's FYP.

The U.S. Army was tasked by DCA to acquire the timing and synchronization subsystem. Because of the widespread availability of commercial timing components, the required equipment was procured off-the-shelf. This equipment provides the requisite (UTC) reference via Loran-C. The JCS Master Navigation Plan (SM-266-83) proposes a phase-out of the Loran system in favor of the NAVSTAR Global Positioning System during the period 1987-1994. Therefore, planning is essential to ensure that the DCS will transition from a system synchronized to UTC via Loran C to one synchronized via other means, of which GPS is a candidate.

III. PRESENT LORAN C BASED TIMING AND SYNCHRONIZATION CONFIGURATION

The present configuration of the timing and synchronization (T&S) subsystem (discussed in detail in reference [1]) consists of the station clock and clock distribution subsystem, described functionally in Figure 1. For terrestrial nodes collocated with DSCS sites, existing cesium beam standards used in the DSCS may be used as the primary reference for the DCS station clock. The two precision oscillators provided as backup will have an initial accuracy equal to the reference and a long term stability of $\pm 2 \times 10^{-10}$ (according to AFCC EPS-82-012, 27 Aug 82). For non-DSCS sites, and where Loran C coverage is adequate, Loran C will be used as the primary reference source for the station clock. Both the DSCS atomic clocks and the Loran C navigational system have transmit frequency sources that are synchronized to UTC.

Loran C was originally selected as the clock source for the near-term DCS T&S subsystem primarily because of its low cost, off-the-shelf availability, commonality with existing DCS timing standards, and proven performance. Loran C is a pulsed, low-frequency (LF), radio navigational system operated by the United States Coast Guard. Use of LF provides propagation stability and low attenuation of the groundwave with distance. Thus, highly stable, long range transmission is possible.

All Loran C transmitting stations are equipped with cesium beam frequency standards. Synchronization among these frequency standards is maintained by monitoring and updating each standard in comparison to UTC as determined by the U.S. Naval Observatory. Loran C is currently available to nearly all DCS sites. The Loran C system as it operates today has demonstrated a 99.7 percent availability, excluding scheduled off-the-air maintenance which reduces that figure to about 99 percent. Frequency accuracy of 1 part in 10^{12} is attainable. Such performance cannot be achieved with independent free-running atomic clocks.

1. STATION CLOCK

The station clock, as functionally depicted in Figure 2, provides an accurate and stable source of frequency and time standards at rates of 1 MHz, 5 MHz, and 1 pps. The station clock has the option of being driven by the Loran C receiver or by an external reference source (such as a GPS receiver or a cesium beam standard), dependent upon the best available reference. In priority order, first choice will be the primary reference; second choice, the alternate reference; and third choice, the two oscillators. The selection of the LORAN C or the external reference source as the primary or alternate reference is an operator selectable function.

2. CLOCK DISTRIBUTION SUBSYSTEM (CDS)

The clock distribution subsystem interfaces with the station clock to generate and distribute timing signals to transmission and user equipments.

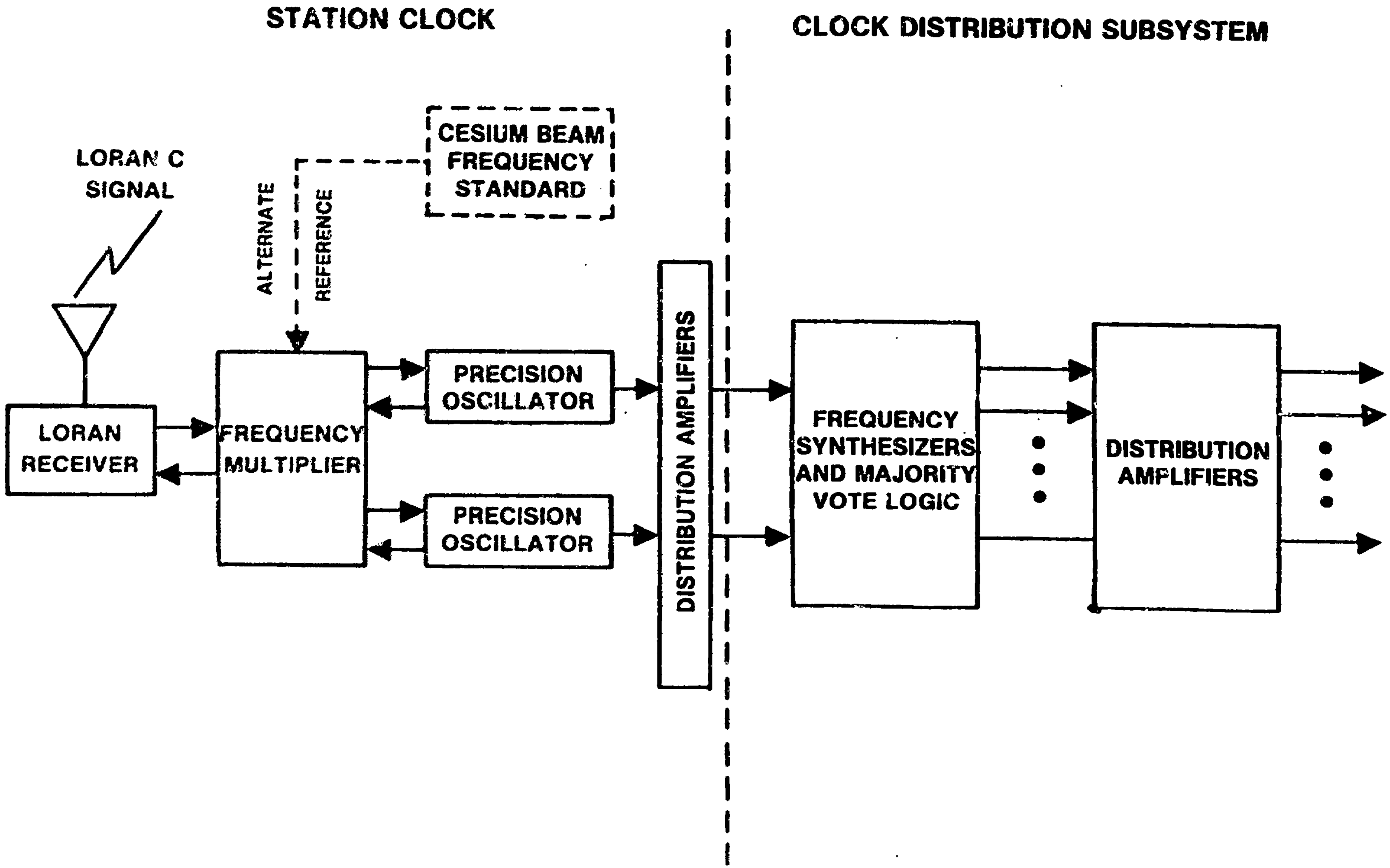


FIGURE 1. DCS STATION CLOCK AND CLOCK DISTRIBUTION SUBSYSTEM

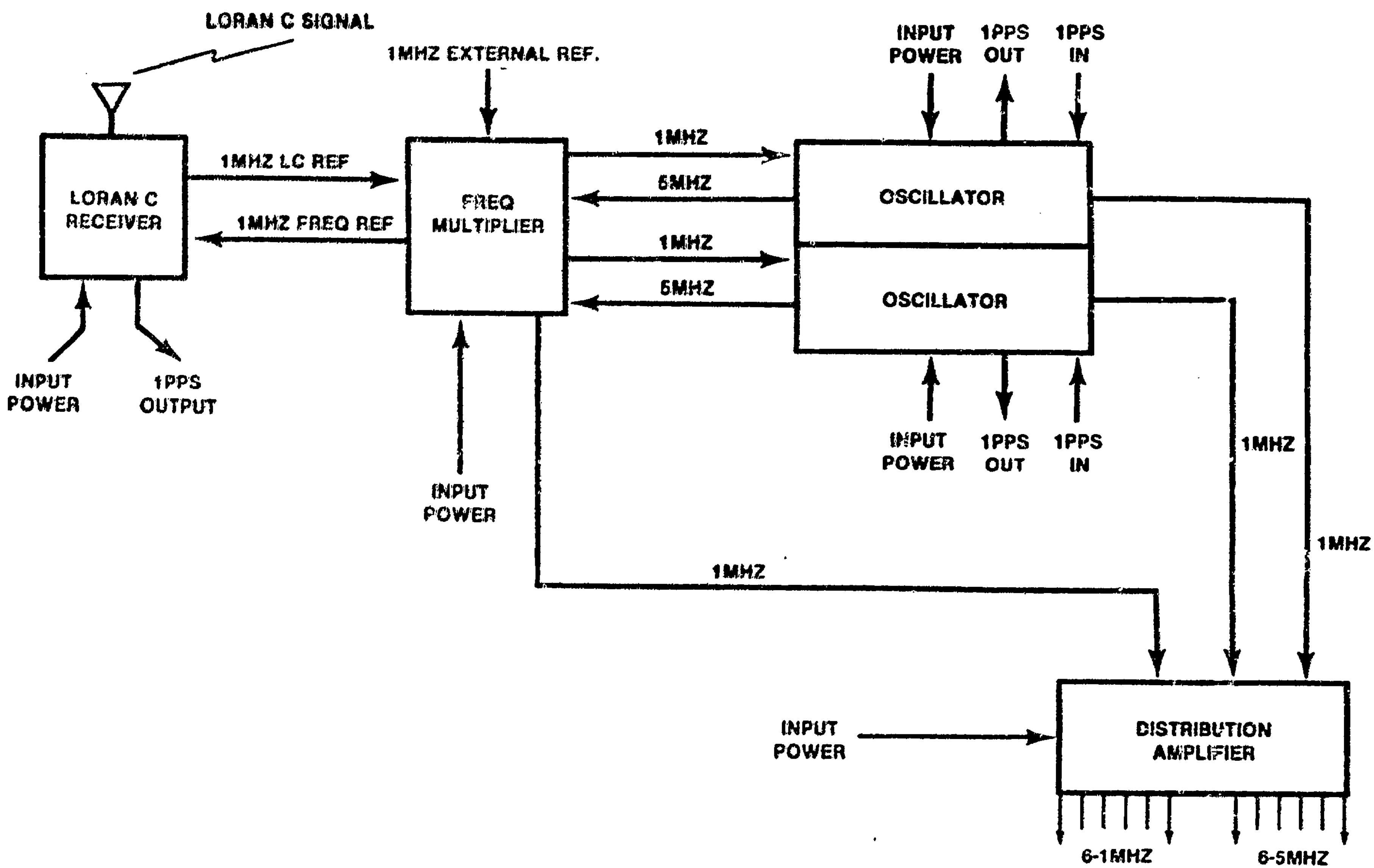


FIGURE 2. FUNCTIONAL DIAGRAM OF THE STATION CLOCK

In order to meet DCS availability criteria, triple redundant frequency synthesis followed by majority vote logic is provided. Voting logic selects one of the three frequency synthesized outputs and provides the selected frequency rate to the distribution amplifier. The distribution amplifier then provides an individually isolated output to each equipment as required.

The CDS and the associated frequency sources provide timing to some or all the transmission and switching subsystems located at a DCS communications node. The clock signals generated by the CDS will be applied to external clock inputs of the transmission and switching equipment consistent with the input interface parameters of each equipment.

IV. DESCRIPTION OF GLOBAL POSITIONING SYSTEM

In order to clarify the implications of the addition of GPS to the DCS T&S system, a detailed description of the NAVSTAR GPS is necessary. This section provides that description.

1. BACKGROUND

The Navy Navigation Satellite System, known commercially as TRANSIT, was developed to support the Polaris submarine fleet. Civilian use was authorized in 1967, promoting TRANSIT's popularity as a source of position. During the early 1970's enhancements to TRANSIT were initiated by the Navy and Air Force to provide more advanced versions of a space-based navigation system. The Navy experiment was called TIMATION, and the Air Force program was called Program 621B. Each of these concepts had certain deficiencies as far as satisfying total Department of Defense (DOD) requirements. TIMATION provided only periodic two-dimensional fixes, while Program 621B required synchronized ground-based transmitters which communicated with transponder satellites. In the summer of 1973, the Defense Navigation Satellite System (DNSS) emerged as an initial plan to develop and deploy a system to meet the needs of the DOD. This concept was subsequently merged with the Navy TIMATION concept, taking the best characteristics of each, to establish the NAVSTAR Global Positioning System. The Air Force was designated the lead military department to develop, test, acquire, and deploy the system to serve the defense positioning and navigation needs.

The NAVSTAR Global Positioning System (GPS) is under development as an advanced Department of Defense satellite navigation system that will provide highly accurate position and velocity information in three dimensions, and precise time and time interval on a global basis continuously. When fully deployed in the 1990's, the system will include 18 satellites providing continuous global coverage with at least four satellites in view at any given location.

GPS has followed the standard Department of Defense (DOD) development cycle: concept validation, full-scale development, and production. The concept validation phase was successfully completed in 1979. Managed by the Air Force Space Division in Los Angeles, California, with active participation by all of the other services and NATO, the program is currently in the field test phase of full-scale development.

During the initial concept validation phase, six satellites were positioned in two orbital planes so that they provide a periodic, three-dimensional navigation capability at a test site in the continental United States. This six-satellite constellation has been maintained in the second phase as support for full-scale development and system tests. In the third phase, the three-plane fully operational system of 18 satellites will transmit three-dimensional navigation signals to users around the world.

2. OVERVIEW

Initially, the Global Positioning System was to deploy 24 satellites, eight satellites in each of three orbital planes. This configuration would provide global coverage with at least four satellites in view. However, due to budgetary reductions, the initial fully operational system of 24 satellites was reduced to 18. The orbital configuration for the 18 remaining satellites and the 3 on-orbit spaces was established to optimize accuracy over the primary areas of interest while minimizing the number of satellites needed to insure continuous coverage. This resulted in the satellite configuration shown in Figure 3 with 18 satellites deployed in 6 orbital planes. The minimum number of satellites required to provide continuous global coverage with at least 4 satellites in view at a given location is 18. Thus a satellite outage in any of the 6 orbital planes could disrupt service over one or more critical areas of the globe. The time required to launch, check out, and place into operation a spare satellite would be unacceptable from an operational standpoint. As DoD, civil, and international users become more dependent on GPS, the resulting lack of global coverage would be even more critical. The ability to quickly reposition one of the on-orbit spares, which has already been checked out and placed into full operation, will be a major asset to the system reliability and availability.

The three interlocking segments making up the NAVSTAR system are the space segment, the ground control segment, and the receiver segment. The space segment transmits accurate satellite position coordinates and timing information; the ground control segment tracks the satellites and corrects their positions and on-board atomic clocks; and the receiver segments processes the position and timing data from the satellites to obtain precise position and velocity readings.

a. Space Segment. The 18-satellite deployment is accomplished in 6 equally-spaced orbital planes (50° apart in longitude and inclined to the equator at 55°). Three satellites will be deployed in each of the six orbital planes with equal spacing of 120° between satellites in a plane. The 3 on-orbit spares will be located in every other orbit plane to provide quick reaction and recovery in the event of a primary satellite failure. The satellites will be in near-circular orbits, at altitudes of about 20,183 kilometers.

The orbital altitude was selected to place the satellites at half-synchronous orbit, in which a satellite makes two revolutions of the Earth per day, thereby causing the satellite to pass directly over the same spot once a day.

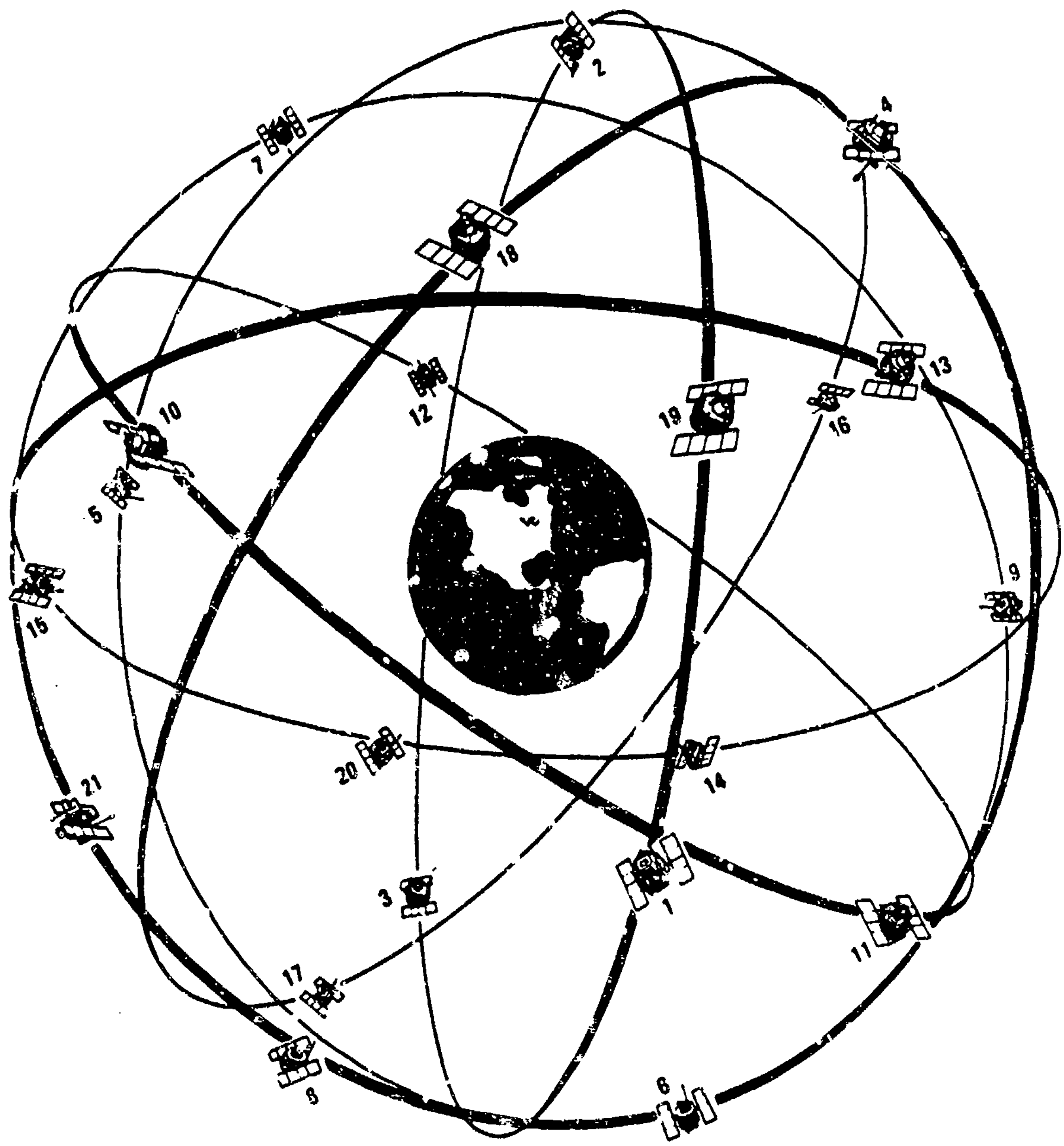


FIGURE3. THE NAVSTAR OPERATIONAL CONSTELLATION
(18 SATELLITES PLUS 3 ACTIVE SPARES)

Their orbit allows each satellite to be viewed (and controlled) by a single control station. Lower orbital altitudes also require less transmitter power from the satellites and make it easier to launch satellites into orbit. And should a satellite be lost, another one will soon appear over the horizon, increasing the system's survivability; GPS survivability will be discussed in a later section of this report.

Between now and the 1990's time frame GPS will be available in a limited form using the preproduction prototypes that were developed during the early phases of the program. The first four satellites, designed for 5-year lifetimes, were launched in 1978, two more in 1980, and another was launched on July 15, 1983. Of these, six are still operational although one of these operates on its quartz crystal oscillator rather than the more stable atomic frequency standard. Three more of these satellites are available for launch aboard refurbished Atlas F boosters. They will be launched only as required to maintain five or six satellites on orbit during the extensive test program now in progress.

b. Ground Control Segment. The GPS ground control segment performs the tracking, computation, updating, and monitoring functions needed to control the satellites in the system each day. Typically this involves Monitor Stations, a Master Control Station, and Upload Stations.

The widely dispersed Monitor Stations employ extremely stable GPS receivers to gather transmitted navigation data from each of the GPS satellites. The location of each Monitor Station is precisely surveyed, and the navigation measurements are combined with additional data on atmospheric conditions. This information is transmitted back to the Master Control Station where precise predictions of satellite ephemerides* and clock offsets are made.

The Master Control Station will process the data received from all of the Monitor Stations to determine the predicted satellite ephemerides and clock bias parameters for each satellite in the system. These data are then used to generate upload messages for each satellite to correct the satellites' navigation messages describing those parameters to the users. The upload messages are then relayed to the appropriate Upload Station for subsequent transmission to the satellites. In this manner, each satellite in the system is provided with updated navigation and timing data at least once a day to maintain system integrity. Provision for mobile master control and upload facilities is also available and will enhance system survivability. Stable atomic clocks and the ability to store long-term ephemeris predictions on board each GPS satellite reduce the need for frequent data uploads. The satellites will be able to operate independently of the ground-based control network for up to a week without degraded performance and for perhaps two to four weeks before becoming unreliable. Still, the ground control segment is the most vulnerable portion of the system and the mobility feature enhances confidence that the system will remain viable during stressed conditions.

*Location of satellite at regular intervals in time.

c. <u>Receiver Segment</u>. Each satellite continuously transmits a unique navigation message that contains the information that the receiver segment requires. The navigation message is broadcast on a 20 MHz spread spectrum signal on a primary frequency L1 at 1575.42 MHz and on a secondary L2 frequency at 1227.60 MHz, coherently derived from the 10.23 MHz atomic frequency standards on-board each satellite.

For position determination, high rate binary codes are superimposed on the carriers, L1 and L2, modulating the phase of the carrier signal. There are two codes on the carrier, a standard positioning service (SPS) or coarse/acquisition (C/A) code with a chip rate of 1.023 Mb/s, and a precise positioning service (PPS) or precise (P) code with a chip rate of 10.23 Mb/s. The highest level of accuracy can be obtained from the PPS. The SPS will be made available to civil, commercial, and other users on an international basis at the highest level of accuracy consistent with the U.S. national security interests. The PPS signal will be encrypted and will be made available initially to U.S. and selected allied military users; limited civil use of the PPS may be authorized if it can be demonstrated that such use is in the national interest, adequate security protection can be provided, and comparable accuracy cannot be obtained from another source.

The codes and their respective carriers are transmitted simultaneously. Both codes will be transmitted on L1. The L2 signal is modulated only by the P-code during normal system operation, but for special applications and testing, the P-code modulation on L2 can be switched to the C/A-code. Both the L1 and L2 signals are also continuously modulated with a navigation data bit stream containing 1500 bits, transmitted at 50 b/s (therefore repeated every 30 seconds), that describes satellite position as a function of time, the state of satellite clock modeling parameters, and other vital information. Besides obtaining position information from tracking the code, a user can determine his velocity by tracking the frequency shift of the carrier--a Doppler effect due to relative motion of the user and the satellites.

The P code is a long sequence, repeating every 267 days, and each satellite is assigned a week-long portion of this sequence. These high-rate, long-duration codes appear essentially as random noise to an observer, hence the term "pseudorandom noise." User acquisition of these codes is accomplished by aligning the same internally generated code with the received code via correlation detectors. The PPS or P-code, as its name implies, provides the fundamental accuracy of GPS. However, unless the user equipment has been provided with both a precision time reference synchronized to GPS time and an estimate of current position (within 3-6 km), direct acquisition and tracking of the code segment for any specific satellite will be extremely difficult. It is necessary in most instances to resort to initial acquisition on the shorter C/A-code.

The C/A code is easy to acquire since it repeats every millisecond. Therefore, it is used to acquire the satellite signal and hand over to the higher rate, longer sequence P code. Each satellite broadcasts a different

C/A code chosen from the family of 1,023 Gold codes, which allows for minimum interference C/A signals from the satellites and thus positive satellite identification and acquisition by the user. As part of the data stream contained in the modulated C/A-code, a Handover Word (HOW) is transmitted every 6 sec, indicating the correct phase point in the incoming P-code associated with the transmitting satellite. Based on this information, the user equipment P-code generator is shifted in phase to synchronize with the incoming P-code at the next change of the HOW.

The navigation message of length 1500 bits transmitted by each satellite includes the following information:

1) Status of the satellite so the user can either accept or reject the data for use in the navigation solution.

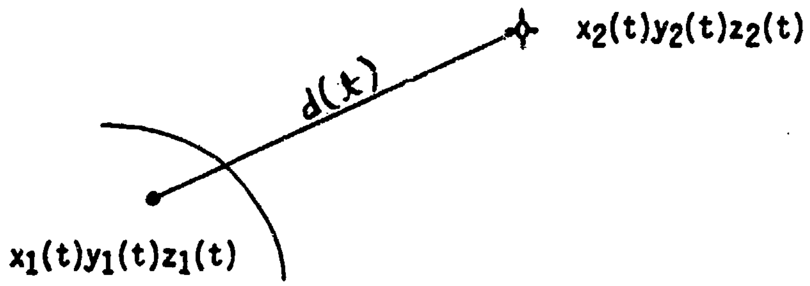
2) The HOW used to determine time synchronization for transfer from the C/A- to the P-code.

3) Satellite clock correction and ephemeris parameters.

4) Parameters for correcting propagation delays through the ionosphere.

5) Almanac information including ephemerides and status of all other satellites in the system.

To transfer time from GPS to a communications station only requires one satellite be tracked. The process for time transfer is straightforward (see Figure 4). Given the position of the ground station and knowing the position of the satellite as a function of time (provided within the received navigation message), the distance as a function of time between the station and the satellite can be computed. The propagation delay of the signal transmission can be calculated as a function of time using the speed of light. The navigation message provides the GPS time at which the signal transmission occurred. By adding the GPS time and propagation delay time, a determination of the GPS reception time is made. Further corrections to the satellite GPS time (or to the derived GPS ground station reception time) are then applied to determine UTC (GPS) time. These corrections are necessary because the reference for the GPS time is an ensemble of three Cesium beam atomic clocks located at Vandenberg AFB, and the satellite clock is not perfectly synchronized to them. Satellite clock modeling parameters contained in the navigation message are used to provide the corrections to account for this. One then applies further corrections to this UTC (GPS) time to calculate the desired UTC (USNO) time. These necessary corrections are computed from data provided within the navigation message which gives the offset between the UTC (GPS) time and the UTC (USNO) time. Until the navigation message is modified to provide this offset, synchronization with the UTC (USNO) must be done manually by obtaining the UTC (GPS)/UTC (USNO) offset over a dialup line to the United States Naval Observatory. The local station clock would then be updated by comparing its output with the corrected GPS receiver output.



$$d(t) = \sqrt{(x_2(t)-x_1(t))^2 + (y_2(t)-y_1(t))^2 + (z_2(t)-z_1(t))^2}$$

$d(t)$ = distance between satellite and ground station at time t

C = speed of light

t_d = propagation delay time

$t(GPS)$ = GPS time of transmission

t_{gnd} = ground station reception time

$x_1(t)y_1(t)z_1(t)$ = dimensional location at time t

$$t_d = Cd(t)$$

$$t_{gnd} = t(GPS) + t_d$$

$$= t(GPS) + Cd(t)$$

$$= t(GPS) + C\sqrt{(x_2(t) - x_1(t))^2 + (y_2(t)-y_1(t))^2 + (z_2(t)-z_1(t))^2}$$

FIGURE 4. GPS TIME TRANSFER PROCESS

A typical GPS system appropriate for a ground station is depicted in Figure 5. The system includes an L-band omni-antenna and preamp, a receiver/processor assembly, and a console for operator control and output display. A high quality crystal oscillator internal to the receiver/processor assembly will provide the required continuous 5 MHz reference and an internally generated 1 pps output synchonized to the UTC (USNO).

The L-band receiver contains the frequency synthesizer, down converter, timing circuits, code generator (for GPS codes), correlator, and a high speed processor for implementation of algorithms for tracking loops and data synchronization. The processor part of the assembly provides the identification of the satellite to be tracked, accepts the navigation message data from the receiver part of the assembly, and computes the propagation delay time to include delays due to ionosphere and troposphere as well as hardware delays. This data is then sent to the receiver for generation of the corrected 1 pps output.

d. GPS Time Transfer Performance. Stanford Telecommunications Inc. built the first operational GPS receiver for the U.S. Naval Observatory. It has been operational since 1980 and has been used to establish the time offset between UTC (GPS) and UTC (USNO). To appreciate the high accuracy of GPS only requires an examination of the initial time transfer for the USNO system obtained during acceptance testing (Figure 6)[3] . These results indicate errors of less than 50 nanoseconds. Contributors to this error include satellite ephemeris, ionospheric and tropospheric modeling, multipaths, and hardware.

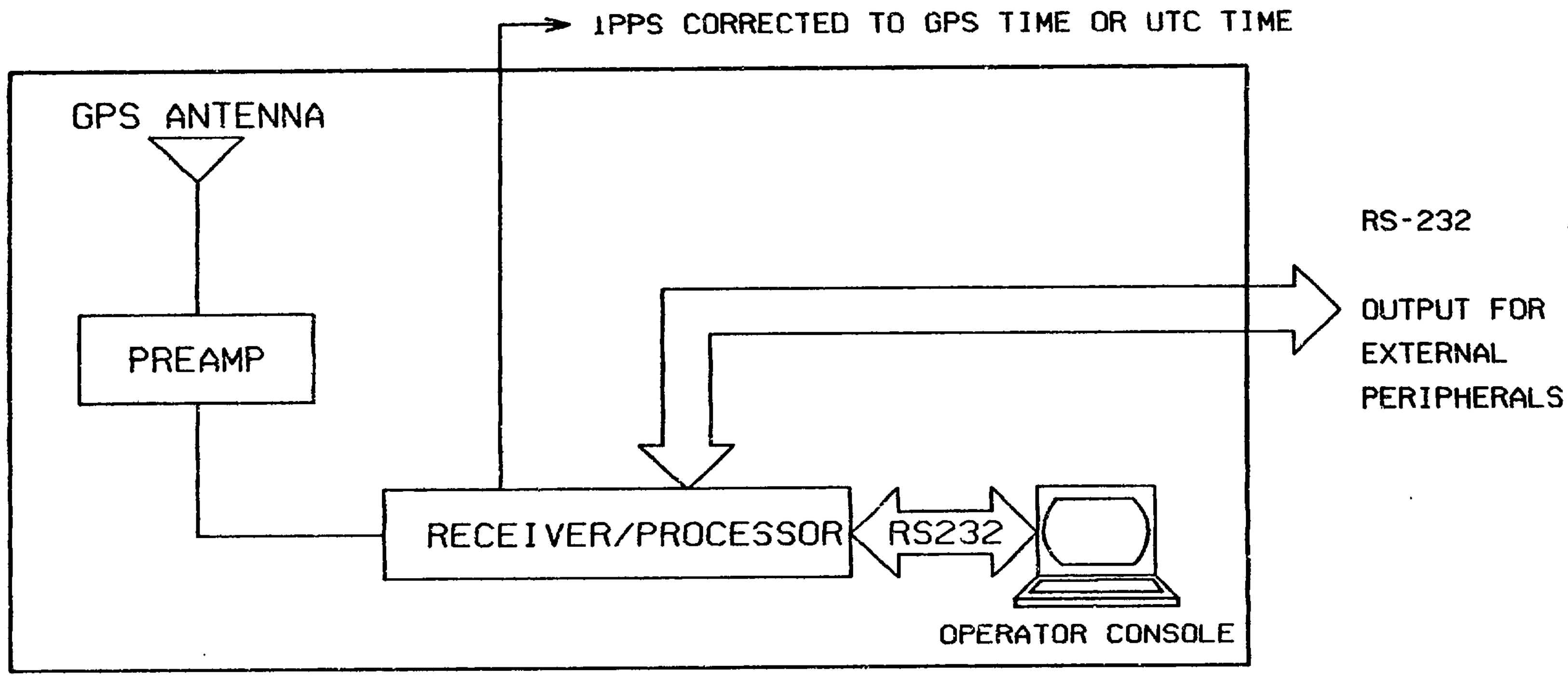


FIGURE 5. TYPICAL GPS TIME TRANSFER SYSTEM FOR GROUND STATION OPERATIONS

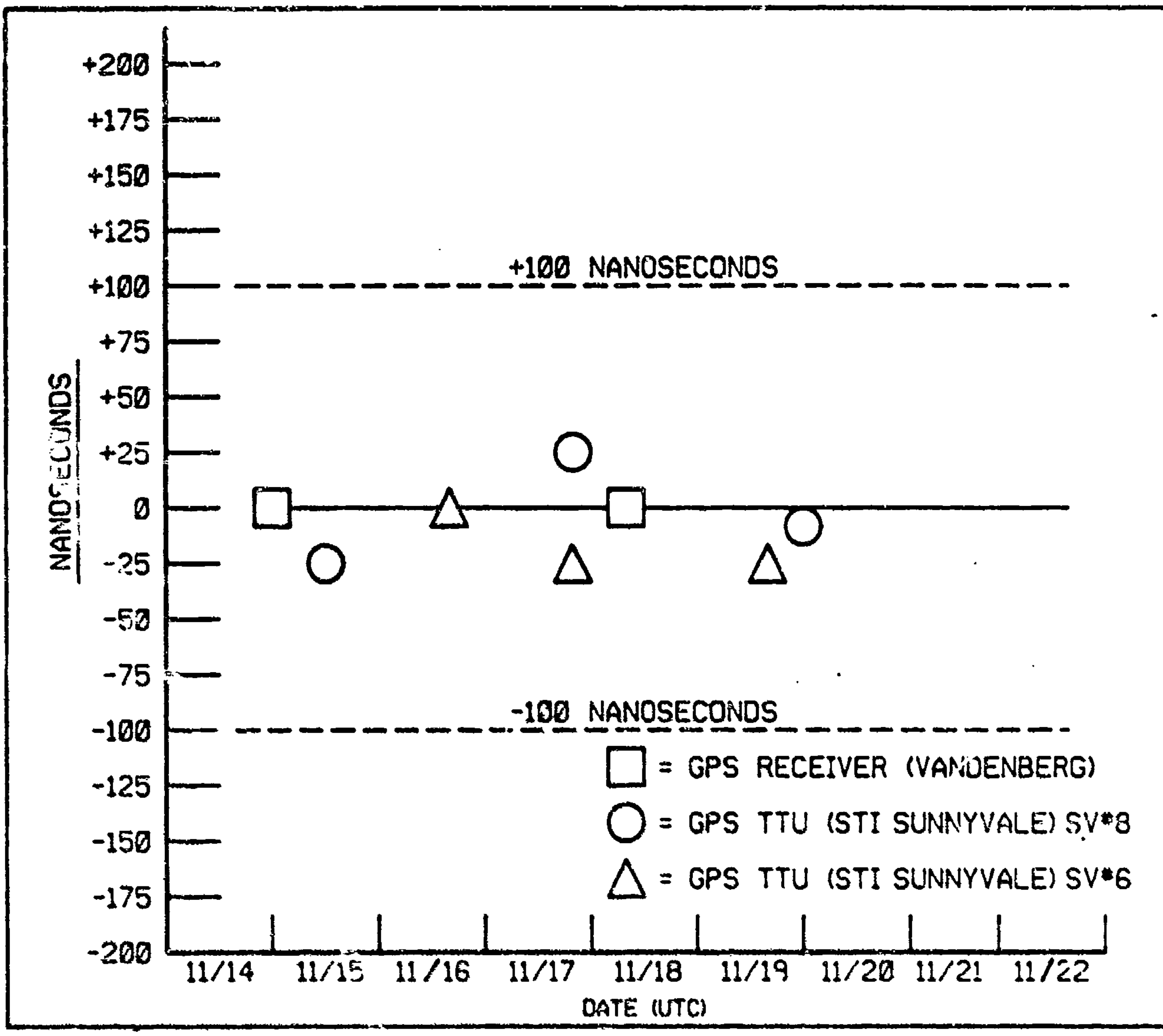


FIGURE 6. TIME TRANSFER ACCEPTANCE TEST RESULTS FOR FIRST OPERATIONAL SYSTEM

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V. SURVEY OF GPS RECEIVERS FOR TIMING AND SYNCHRONIZATION

Several types of receivers have been developed by the Department of Defense, other government agencies, and by industry. Early in the Phase I program, a "low cost" unit was being developed by DOD in which performance was traded for cost at every possible turn. One example of this tradeoff was the use of only the C/A-code instead of the inherently more accurate P-code implementation. The intent was to place this equipment into operational use at the earliest possible date, using as few as nine satellites to provide global coverage. Unfortunately, deployment of these units was scrapped since the vast majority of potential DOD users wanted to wait for the more sophisticated equipments and the full system deployment.

The next type of receiver in the performance ladder was the one- or two-channel P-code version. This implementation again sought to reduce cost by minimizing the number of modules required while retaining the performance of the P-code.

The most sophisticated units employ four channels to make continuous pseudo-range measurements to four satellites, and a fifth channel to facilitate acquisition of new satellites and perform the ionospheric calibration function. Both the one or two channel P-code version and the four or five channel version can be aided by external inputs such as a digital altimeter (to eliminate one of the unknowns in the three-dimensional position solution) or a precise clock synchronized to GPS time to eliminate the receiver time bias error.

Among the GPS units developed by other government agencies are: a satellite-based unit called GPS-PAC developed jointly by the Defense Mapping Agency and NASA for flight aboard LANDSAT; a GPS time receiver developed by the U.S. Naval Observatory to tie into its bank of cesium frequency standards; and another attempt at development of a low-cost GPS unit, this time sponsored by the Department of Transportation and aimed at potential civilian use. Some of the commercially developed GPS receivers are discussed in detail in Appendix A.

VI. USE OF GPS FOR DCS TIMING AND SYNCHRONIZATION

1. TIMING CONSIDERATION

In the previous sections of this report, we discussed GPS as a revolutionary means of positioning and navigation. It is also a means for disseminating precise time and time interval throughout the world. However, GPS is not tied directly to Coordinated Universal Time (UTC). This is due to the fact that approximately once a year an extra "leap second" is inserted (or deleted) to bring UTC according to atomic clocks into synchronization with earth time. To change GPS time by adjustment of its clocks would destroy the precision of the GPS navigation and positioning activities that might be in progress at that time. Therefore, each satellite carries four atomic clocks, two cesium and two rubidium.

Development of these space-qualified clocks was accomplished in three phases. Since they were more readily available in the size and ruggedness required for space application, rubidium frequency standards were used exclusively in the initial GPS satellites. In parallel, a major effort was initiated to develop and space-qualify the more stable cesium standard. Finally, after testing both the rubidium and cesium standards aboard GPS satellites, the third phase of the clock development effort involved even more advanced design of the cesium standard for use in the operational satellites.

Although data on the exact performance of these advanced space-qualified clocks are not generally available, it can be expected that they will routinely achieve fractional long-term frequency stability in the range of a few parts in 10^{14} per day. This long-term stability is one of the keys to the operation of GPS, since it allows the synchronized generation and transmission of the navigation and timing signals on board each of the GPS satellites, without continuous monitoring from the ground. Conclusion: acceptable performance for DCS (better than Loran). The performance attainable using GPS is better than that provided by Loran and is thus acceptable for DCS applications.

2. SYSTEM SURVIVABILITY

The ability of GPS to generate timing signals in the face of hostile actions is of great interest to the DCS community. It is indisputable that the system is vulnerable; it can be jammed, the satellites can be eliminated, and the control stations are open to sabotage. However, many design aspects of the system were selected expressly to reduce system vulnerability. As a result, the system should be quite robust through tactical engagements.

The GPS satellites could conceivably be attacked. However, at their high altitude orbits, it would take a rather large booster to rendezvous. Furthermore, one of the reasons the satellites were placed in half-synchronous orbits rather than in geosynchronous orbits was to provide graceful degradation; that is, if one or several satellites were eliminated, several more would soon arise over the horizon. Orbital spacing has been carefully planned so that a single detonation could not make substantially multiple "kills" at nodes where orbits cross. Finally, the satellites are equipped with a certain amount of nuclear and laser hardening. The control stations are the next part of the system subject to removal. The features to minimize this vulnerability include physical location and signal protection. All of the control segment facilities are located on U.S. soil, including the remote monitor stations, and the control elements are redundant to avoid loss due to single strikes. The upload messages use encrypted spread spectrum signals to prevent reception by others and to make deliberate interference difficult. Even if uploads are ceased for a period of time, the satellites will continue to broadcast with a slow buildup of error as their clocks drift.

GPS receivers are susceptible to jamming from powerful noise sources. However, the spread spectrum signal is very effective in minimizing the effects of jammers; while the GPS signal is "despread" in the receiver, the jammer signal is similarly "spread."

Thus while GPS is vulnerable in many ways to hostile actions to deny its use, it would take a very intensive, expensive, and even strategic operation to significantly degrade its effectiveness. This is due in part to the on-orbit space satellites.

The on-orbit spares provide some degree of survivability and robustness. In addition, each satellite will have provisions to offload power from satellite systems in a predetermined manner to prevent catastrophic failure and to insure continued operation of critical navigation functions. In the event that the on-board navigation system computer processors are upset by pulses from a nuclear burst, the satellites will have the ability to conduct on-board diagnostics and correct or reset data automatically. Finally, the satellites are capable of operating in a virtually autonomous manner due to the inherent stability of the on-board clocks, the ability to process data, and the long-term ephemeris prediction capabilities built into the system design. Therefore, it should be possible to insure continued operation of the system via a deployable or mobile control segment that can be brought on-line as needed and that is capable of performing minimum essential housekeeping functions.

With the 18-satellite baseline plus 3 on-orbit spares, there will be short "gaps" in coverage at the mid and high latitudes due to geometrical effects. Table I illustrates the number of hours of coverage per day for selected locations.

3. INTEGRATION OF GPS INTO EXISTING DCS TIMING SUBSYSTEM

a. Technical Interface. As mentioned previously, the GPS can provide the primary reference directly to the station clock. This is accomplished by including a GPS receiver with the other complement of equipment previously discussed. The appropriate output of the GPS receiver is then fed into the frequency multiplier within the current T&S equipment, as shown in Figure 7. The frequency multiplier provides the functions of frequency synthesis, distribution, manual selection and failure mode operation and all necessary interfaces within the station clock, to include the GPS receiver, the Loran C receiver, the primary and backup oscillators, and the distribution amplifier.

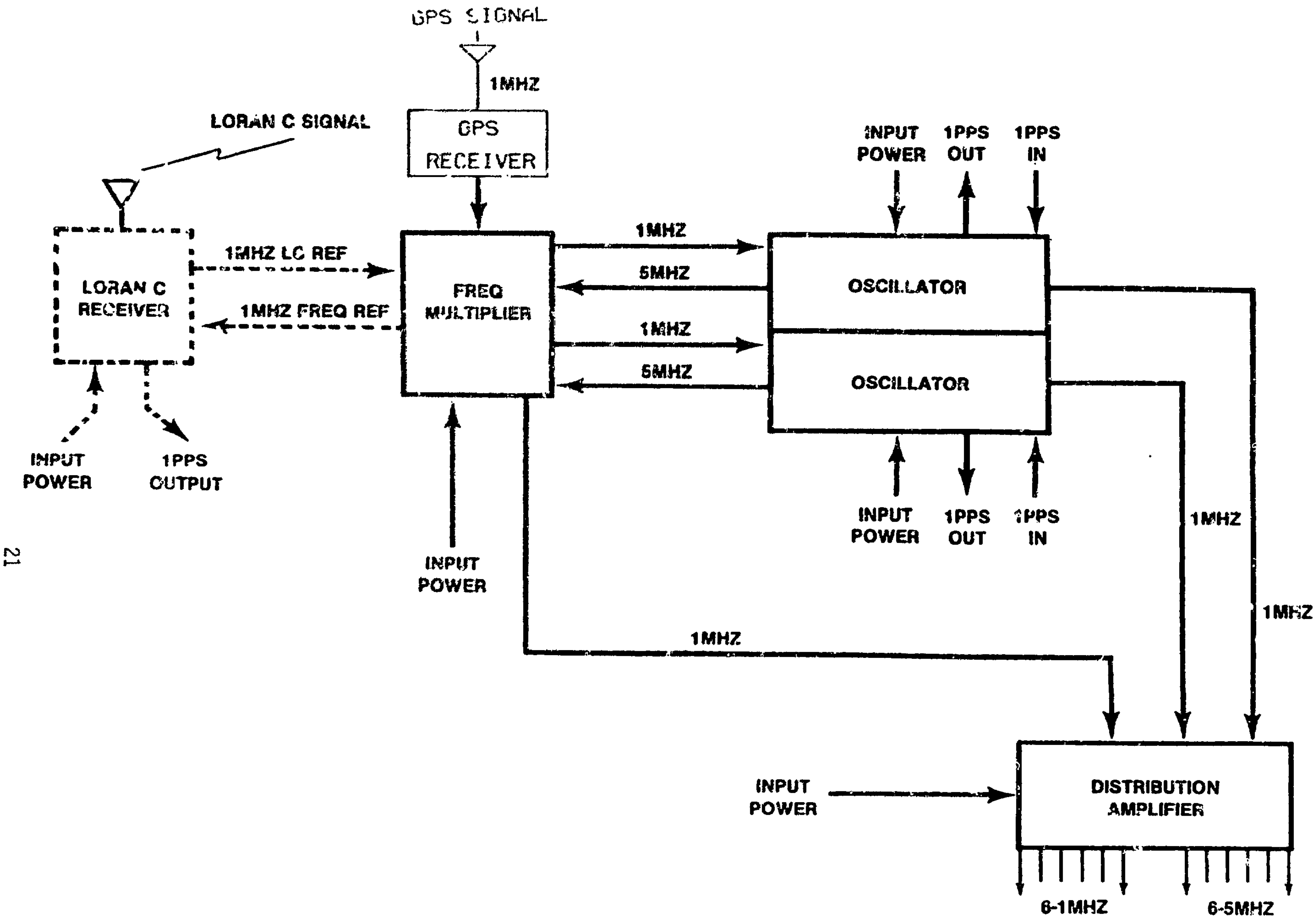

FIGURE 1. FUNCTIONAL DIAGRAM OF THE STATION CLOCK

Should the primary reference fail (in this case the GPS receiver), the frequency multiplier will automatically switch to the alternate reference (Loran C). The frequency multiplier will then continue to operate using the alternate reference until it is manually reset. Should both the primary and alternate references fail, all reference input signals to the oscillators will discontinue, and the oscillators will operate unlocked (not phase and frequency locked to the primary and alternate references).

b. Projected Implementation. The implementation of the timing and synchronization equipment previously discussed is currently ongoing and will be spread across a number of years (begun in late 1983 and scheduled for completion in the 1990's). The current implementation is Loran C based equipment; however, as GPS becomes operational, adjustments in the implementation strategies will be made.

The Department of Defense published the following notice in the Federal Register (50 FR 40991) 8 Oct 1985:

> The Department of Defense has placed a research and development (R&D) constellation of navigation satellites in orbit that are the forerunners of an operational Global Positioning System (GPS) constellation of 18 satellites plus three on-orbit spares. The R&D constellation is essential to the development of the satellites, military user equipment, and ground control facilities. During the development phase of the GPS, the R&D satellites will transmit signals which are intended only for military testing purposes.
>
> When the GPS is declared fully operational, an event that is scheduled to occur in late 1988 - early 1989, the DoD intends to provide GPS Standard Positioning Service (SPS) to any user, worldwide, at an accuracy within the limits of national security considerations. The current accuracy that is planned for the SPS is 100 meters, Two Distance Root Mean Square (2 DRMS). There is no plan to charge users for this service.
>
> In the meantime, the signals from the R&D satellites are subject to change without advance warning, may transmit non-useable altered signals for government testing, and may be turned on and off at any time. Therefore, any use of the GPS R&D satellite signals for positioning, navigation, time transfer, or any other purpose (which may be considered or which might be ruled by law as operational, or relied upon as such), is not authorized by the U.S. Government and will be at the risk of the user.

Based on the above Department of Defense notice and the question of launch schedule for GPS satellites, it is readily apparent that GPS will not be available before the early 1990's. Based on a review of those DCS nodes where timing and synchronization equipment will be implemented, only 11% of the DCS would still require timing and synchronization equipment in 1992, assuming GPS becomes operationally available in that year. Therefore, it is clear that the application of GPS within the DCS will be evolutionary in nature. Those sites implemented with Loran C based equipment would be retrofitted with GPS receivers to initially complement the present Loran system and later, as Loran C is phased out, become the DCS primary reference source.

VII. CONCLUSIONS

GPS, when fully operational, will provide the timing and synchronization characterstics necessary to meet the objectives of the DCS. Even though there has been a delay in launching the GPS satellites, commercial vendors have continued to develop and manufacture GPS receivers. Therefore these GPS receivers are currently commercially available off-the-shelf. However, because data on the exact performance of these GPS clocks and receivers are not generally available, a formal test and evaluation should be performed. The U.S. Army Information Systems Command (Ft. Huachuca, AZ) has done some preliminary evaluation on the applicability of GPS for a small number of near-term requirements lacking Loran C coverage. A field trial of candidate GPS receivers would also be recommended. The U.S. Air Force Communications Command (Scott AFB, IL) has begun work on the preparation of an equipment performance specification for the acquisition of a GPS receiver for use within the DCS.

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LIST OF ACRONYMS

C/A - Coarse Acquisition

CDS - Clock Distribution System

DNSS - Defense Navigation Satellite System

GPS - Global Positioning System

HOW - Handover Word

LSTDM - Low Speed Time Division Multiplexer

P - Precise (code)

ppm - Pulses Per Minute

PPS - Precise Positioning Service

pps - Pulses Per Second

SPS - Standard Positioning Service

T&S - Timing & Synchronization

USNO - United States Naval Observatory

UTC - Coordinated Universal Time

APPENDIX A

As the GPS has evolved, a large number of commercial vendors have developed GPS receivers with a wide-range of characteristics. The following pages provide a short description of a representative sampling of the available commercial GPS receivers. These descriptions are followed by a matrix comparing the receivers as to: (1) allowed operational code type, (2) time and frequency inputs, (3) timing and frequency outputs, (4) remote accessibility, (5) AC/DC power options and (6) environmental considerations including operating and storage temperatures. Blanks within Table A-1 are due to the unavailability of the information. The current typical cost of these receivers ranges between $15,000 and $25,000. However, it can be anticipated that as GPS evolves and the growth of receiver production and sales increases, the cost will be reduced.

A.1 Trimble Navigation

Model 5000A GPS Time Frequency Monitor

The Trimble 5000A provides high accuracy timing and frequency monitoring based on the NAVSTAR GPS. The 5000A operates on the civilian L-Band, C/A code transmissions from NAVSTAR. Time and frequency are determined from satellite transmissions and calculations referenced to UTC through the GPS Master Clock system which provides traceability to UTC and all international time scales utilizing NBS, USNO, and BIH publications.

The Trimble 5000A automatically acquires and tracks the scheduled satellite for time and frequency determination after accurate position first determined by sequentially tracking four satellites. Time, frequency, satellite position data and status, and tracking schedules are output through an RS-232C interface. Manual control from the front panel keyboard and remote control through the RS232C are available and provide maximum ease of use.

Time and frequency inputs/outputs are available on the rear panel. Timing outputs (1 pps and 1 ppm) are synchronized during tracking intervals and provide a timing accuracy of 200 ns with respect to UTC. Frequency outputs (5 MHz) are isolated, buffered outputs from the input 5 MHz frequency reference.

The Trimble 5000A consists of a seven inch high rack mountable unit, an antenna/preamp, and coaxial cable for interconnection. The units can be powered from 115/230 VAC or 20-35 VDC with internal batteries available for up to one hour of built-in standby power with automatic switchover to battery when AC or DC primary power fails.

A.2 Texas Instruments

Model TI 4100

Data collected simultaneously from four satellites are processed by the TI 4100 GPS receiver to solve for the three dimensions of position, velocity, and time. If altitude is known or if an external time standard is used, the TI 4100 produces a navigation fix using only three satellites. With both time and altitude known, two satellites will provide latitude and longitude information.

The TI 4100 automatically operates using the P-code, and has the versatility to also operate using the C/A - code in the absence of the P-code. Flexible input/output capability exists for special applications requiring an interface with other systems using RS232 format.

The TI 4100 provides a one pulse per second output synchronized to GPS time to provide an accurate time marker for coordinating GPS data with data from other systems. An input port is also available for synchronizing the TI 4100 with another system.

The Texas Instruments 4100 consists of a 9 inch high, rack mountable receiver, an antenna/preamp, and cable for interconnection. The power requirement is 22-32 VDC.

A.3 AUSTRON

Model 2101

The Austron 2101 GPS receiver has been designed to capture the ultimate accuracy of the NAVSTAR GPS system using the C/A-code transmissions. The receiver is fully microprocessor controlled and will permit the user to compare his local 1 pps, to GPS time or UTC time and generate an ontime 1 pps. It will also accept input frequencies of 1, 5, or 10 MHz from the user's local frequency standard. (Compatible with Austron's GSQ-215 (DCS Station Clock)).

The Austron 2101 can be controlled manually using the hex key pad. Remote monitoring of the equipment is accomplished using a full duplex RS-232 serial interface via a telephone modem. Local printer connection is made via the RS-232 printer port.

The output frequencies consist of 1, 5, or 10 MHz square waves. The Model 2101 is approximately 6 inches high, rack mountable, and is used with an antenna/preamp and interconnecting cable. Power requirement is satisfied by 115/230 VAC.

A.4 DATUM

Model 9390 GPS Time/Frequency Monitor

The 9390 GPS Time/Frequency Monitor employs C/A code transmissions from satellites in the NAVSTAR GPS to provide time and frequency transfer data. The 9390 requires the presence of only one satellite for time and frequency monitoring, providing the geographical coordinates on the receiver location are known.

Operation of the DATUM 9390 is controlled locally from the front panel keyboard. Remote control capability and printer interfacing are provided by an RS-232 I/O port. All manual control selections and parameters are retained in nonvolatile memory.

Completely self-contained except for separate antenna/preamp and interconnecting cable, the 7 inch high 9390 is designed for mounting in a standard 19-inch equipment rack. Primary power can be provided from either 120-240 VAC or 20-35 VDC power sources.

Two isolated corrected 1 pps outputs and a single corrected 1 ppm output are available on the rear panel. Frequency outputs consist of two isolated, amplified outputs from the frequency inputs (1, 5, or 10 MHz). Compatibility of the DATUM 9390 with the GSQ-215 DCS Station Clock has been demonstrated by the U.S. Army Information Systems Engineering Command Ft. Huachuca, AZ.

A.5 Stanford Telecommunications Inc.

Model TTS-502B

The STI Time Transfer System TTS-502B provides the capability of worldwide time transfer with an accuracy of better than 100 ns relative to GPS time. The TTS-502B operates from the C/A-code transmissions from NAVSTAR.

The TTS-502B provides an RS-232C port for data output to external peripherals. The receiver also can provide a 1 pps output, corrected to GPS or UTC, and coherent 5 MHz and 1 MHz sinewaves.

The TTS-502B consists of the receiver, antenna/preamp, and associated cable. The primary power is 115 VAC.

A.6 KINEMETRICS

Model GPS-DC

The Kinemetrics/TrueTime Model GPS-DC Synchronized Clock has been specifically designed to provide extremely precise UTC time in the forms necessary to fit the widest variety of applications. Besides visual display, each clock provides IRIG-B time code, RS-232 interface, and a 1 Hz reference pulse as an ultra-precise time base. In addition to these standard functions, a host of optional time data functions are available including Parallel BCD and IEEE-488 interfaces, IRIG-E, IRIG-H time codes, and time difference measurement.

Each Model GPS-DC provides a 5 MHz square wave output, steered by the GPS Satellite constellation. Each clock also can determine the geodetic location (latitude, longitude and altitude) of its antenna within 25 meters spherical error probability. The measurement data obtained is presented on the visual display and on certain optional outputs.

A.7 COLLINS

Model NAVCORE I

Collins NAVCORE I GPS receivers are available in two versions. A time-only unit is available for static applications which requires only the precision of GPS time. The NAVCORE I navigation unit provides complete dynamic position, velocity, and time outputs. The NAVCORE I receiver computes 3-D position information and time from four satellites or from three satellites if the user provides an altitude input.

The receiver provides Coordinated Universal Time (UTC) accurate to within 250 nanoseconds anywhere in the world. UTC is synchronized between the GPS master control ground stations and the United States Naval Observatory, the Paris Observatory, the U.S National Bureau of Standards and other international users.

Two different-size packages are available for either the time-only or navigation versions of NAVCORE I products. Each has identical circuit cards and RF module. Both the single-module standard package and the 'low profile' package (consisting of two modules) have a volume of less than 269 cubic inches and weigh less than 8 pounds. The low-profile package can be mounted in a 19" rack module only 3 1/2"high.

Inputs and outputs include a standard RS-232C interface (9600 baud data line), antenna power, and a one pulse per-second timing output.

The Collins NAVCORE I receivers are designed to exceed 5000 hours Mean Time Between Failures (MTBF) when operated within the specified environmental ranges.

A.8 Allen Osborne Associates

Model TTR-5 GPS Time Transfer System

The TTR-5 features time transfer based on the C/A-code transmission from NAVSTAR which allows it to provide precise UTC or GPS timing data. Data memory and time retention are possible with power off.

The TTR-5 allows for unattended operation through an RS232 communications port. The RS232 port provides two-way data transfer and device remote control as well as for printer interfacing.

The TTR-5 consists of an 8 inch high receiver, antenna, and interconnection cable. The primary power is 115 VAC.

	Trimble Navigation 5000A	Texas Instruments TI4100	Austron 2101	Datum 9390	STI TTS-5028
Code Type	C/A	C/A or P	C/A	C/A	C/A
Inputs					
Time	1 pps		1 pps	1 pps	1 pps
Frequency	5 MHz		1,5, or 10 MHz	1,5, or 10 MHz	5 MHz
Outputs					
Time	1 pps/ 1 ppm	1 pps		1 pps/ 1 ppm	1 pps
Frequency	5 MHz		1,5, or 10 MHz	1,5 or 10 MHz	5 MHz
Remote Control	RS232C	RS232C	RS232C	RS232C opt. IEEE 488	RS232C
Power					
AC	115/230V		115/230V	120/240V	115V
DC	20-32V	22-32V		20-35V	
Environmental					
Operating Temp	0-50°C	-20-50°C	0-35°C	0-50°C	
Storage Temp	-20-75°C		-20-70°C	-20-60°C	

	Kinemetrics GPS-DC	Collins Navcore I	Allen-Osborne Associates TTR-5
Code Type	C/A	C/A	C/A
Inputs			
Time			
Frequency		1,5, or 10 MHz	
Outputs			
Time	1 pps	1 pps	
Frequency		5MHZ	
Remote Control	RS-232C	RS-232C	RS232C opt. IEEE 488
Power			
AC	95/135V (190/270V)		115V
DC	11-28V	10-40V	
Environmental			
Operating Temp	0-50°C	-20-55°C	-10-50°C
Storage Temp			

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